The Effects of a Single Season of Play on the Knee Cartilage Health of NCAA Football Linemen

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Honors Research Distinction in the Department of Mechanical Engineering at The Ohio State University

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2015

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Abstract

Articular cartilage covers the ends of bones where they come together to form joints; thereby supporting the joints under applied loads and allowing a full range of motion. Cartilage has a limited ability to self-repair however, and over time, areas of localized damage, or cartilage defects, can cause pain, stiffness, and loss of functionality. Football linemen in particular are at an increased risk for knee cartilage defects and early-onset osteoarthritis (OA). Therefore, the purpose of this project is to determine which factors predict or indicate changes in the knee cartilage health of NCAA football linemen over one season. 15 linemen were recruited for this study and each participated in the preseason evaluation. Only 12 of the players, however, returned for the postseason session. Each evaluation included magnetic resonance images (MRI) of each knee, 6 self-administered surveys, and walking trials in a motion capture lab. Player profiles are used to organize this information which includes quantified MRI scores, self-reported clinical assessments on quality of life, and biomechanical parameters from gait analysis from each evaluation. Of the 12 players who returned for postseason evaluation, only 8 provided complete profiles and 2 of these experienced a decline in knee cartilage health over the season. Sets of independent survey and kinematic variables were grouped and compared using a sequence of stepwise and general regression tests to determine which variables correspond to changes in cartilage health. The results of this study show the possibility of overarching trends among subjects with similar cartilage health, but a larger study could provide more conclusive information about the relationships among changes in MRI, survey scores, and gait kinematics. This study should include a larger number of participants over a number of years to fully capture the changes in self-determined well-being and movement patterns that influence changes in knee cartilage health in NCAA football linemen.

Acknowledgements

First and foremost, I would like to thank my advisor, Dr. Robert Siston. You constantly encourage me to better myself and accept nothing less than my best work. You have pushed me out of my comfort zone and allowed me to learn an incredible amount about myself along the way. Over the past few years, you have inspired my curiosity and helped me find new interests and skills that I never anticipated.

Also, thank you to Dr. Rebecca Lathrop-Lambach for your exceptional work on this project. Without the foundation you laid out, my contribution would not have been possible. Thank you for taking the time to explain different concepts and teach me about new topics. You taught me to ask research questions and work to understand my results rather than just accepting them as the answer.

Rachel Baker, thank you so much for your help as I worked through the stats for this study. Thanks for giving me a crash course in statistics and answering all of my questions! Your input was invaluable to this project and I cannot thank you enough.

I would also like to thank the entire NMBL lab. From the first lab meeting I attended, I felt welcome and was impressed by the collaboration within the lab. Your input at all points throughout this project has been absolutely invaluable, and I truly appreciate your constructive feedback on presentations and written papers. You are incredible role models and I am thankful for your help over the past few years.

Thank you to my friends, who have been an incredible support system throughout our time as undergrads. Whether we are struggling through classes, navigating the world of research, or finding time to enjoy college, you help me keep my life in balance and enjoy the ride. Thank you for helping me sort through piles and piles of data, listening to a few too many practice

presentations, and being by my side at every point throughout this journey. Without you, I could not have accomplished any of this!

Finally, I would like to thank my family. Alex, you are the reason that this project initially caught my eye. Thank you for teaching me to love football and understand that linemen are by far the most important part of any team. Mom and Dad, thank you for your unconditional love and support. You have helped me face my fears, work through my challenges, and have always been the first to help me celebrate my successes. Thank you just isn't enough for all you do. Love you guys!

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Chapter 1: Introduction

Articular cartilage covers the ends of bones where they come together to form joints. This cartilage helps to support the joint under applied loads and allows for a full range of motion. Due to its avascular nature, however, cartilage has a limited ability to self-repair. Therefore, articular cartilage is susceptible to areas of localized damage, often called cartilage defects or “potholes” (Figure 1). These defects can lead to pain, stiffness, and a loss of joint functionality [1]. In addition, cartilage defects can lead to conditions such as osteoarthritis (OA) in the long term [2].

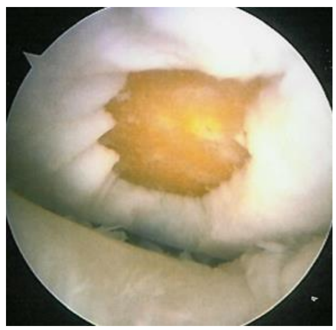

Figure 1: "Pothole" cartilage defect in the articular cartilage of the knee [3]

While the exact cause of cartilage defects is not known, there are different conditions known to increase the likelihood of cartilage damage. Individual-specific characteristics such as abnormal joint anatomy, joint instability, and inadequate muscle strength or endurance can leave the knee susceptible to cartilage damage. In addition, direct blunt trauma, impact loading and excessive torsional loading of joint can cause damage to cartilage without influencing the underlying, or subchondral, bone [4]. An example of a direct blunt trauma for a football player may include a direct blow to the knee, possibly with another player’s helmet. Torsional loads can be applied to the knee joint as players cut, or quickly change direction, and pivot during the course of a play.

Cartilage defects progress by one of two main mechanisms based on size. Smaller cartilage defects are subject to excess stress around their outer edge [5]. The applied pressure is concentrated around the rim of the defect, but nearly zero at all points inside the defect area, (Figure 2). Over time, the rim cartilage dies due to this increased stress, detaches from the bone, and moves away from the original attachment point. This allows the defect to progress and increase in size.

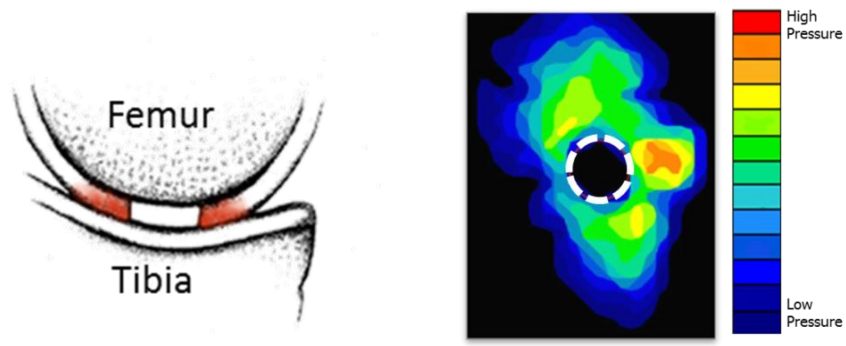

Figure 2: Small full-thickness knee cartilage defect and the corresponding pressure profile (Courtesy of Andrea Adams, NMBL)

Larger defects, however, are more likely to progress due to contact with the subchondral bone [5]. In these cases, the area within the defect boundary experiences nonzero stress levels (Figure 3). Over time, the pressure on the subchondral bone limits the blood flow to the area and therefore causes the subchondral bone to calcify. When this happens, the articular cartilage detaches from the bone's surface which increases the area of the defect. This process can result in bone-on-bone contact, causing great discomfort and even further degradation of the joint health.

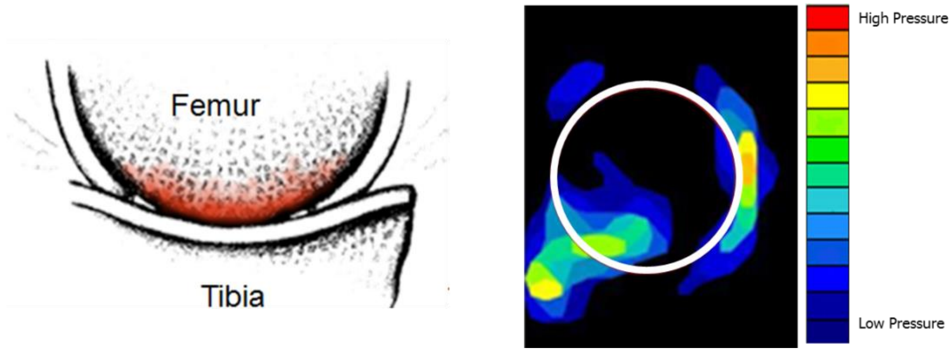

Figure 3: Large full-thickness knee cartilage defect and the corresponding pressure profile (Courtesy of Andrea Adams, NMBL)

Previous work has shown that football players, especially linemen, are at an increased risk for cartilage defects compared to the general population [6]. In one study, 64% of NFL retirees were observed to have articular cartilage abnormalities and 32% of retired linemen showed full thickness defects after their playing careers ended [7]. Another study showed that retired football players, specifically linemen, are likely to develop severe, early-onset OA [8]. In work by Golightly, et al., almost 48% of NFL retired linemen had OA before the age of 60, while those who played other positions had a 41% risk of the same condition before 60 [8]. These differences are believed to be due to the high incidence and severity of knee injuries incurred by linemen during their playing careers [8]. While this work has explored the long-term effects of playing football, little is known about the short-term effects of each additional season of play.

1.1 Focus of Thesis

The purpose of this project is to determine the factors that either indicate or predict changes in the knee cartilage health of NCAA football linemen. Three separate groups of information were used for this analysis: magnetic resonance images (MRI) of each knee, self-administered surveys, and kinematic parameters from walking trials in a gait lab. These quantities were used to perform three discrete comparisons (Figure 4). Comparison 1 examines how the outcomes of the clinical quality of life assessments chronicle gait changes in MRI from pre to postseason. Comparison 2 explores the relationship between the kinematics and the outcomes of the self-administered surveys. Finally, Comparison 3 investigates how the kinematics from walking trials correspond to changes in knee cartilage health as represented by MRI.

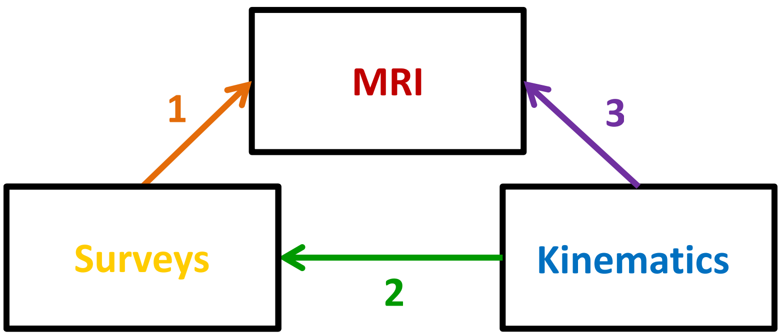

Figure 4: Outline of paired comparisons

1.2 Significance of Research

Extensive work has been done to explore the long-term effects of football on the knee cartilage health of linemen [6, 7]. Little work however, has been done to explore these changes in the short-term, especially over the course of a single season. These short-term results may be indicative of the causes and progression of articular cartilage defects in the knee.

This work is an extension of a previous study which investigated the measurable biomechanical parameters believed to influence articular cartilage degeneration [9]. This work utilized pre and postseason MRI classifications as well as the preseason kinematics from trials in the motion capture laboratory. The motion capture trials include walking, jogging, squating, and 3 lineman-specific motions to generate a robust base of kinematic information. It was found that increases in peak ground reaction forces along with increased adduction and abduction moments were indicative of potential declines in knee cartilage health.

This study incorporates the change in MRI classification from pre to postseason as well pre and postseason kinematics and self-administered clinical assessments in an effort to either predict or indicate changes in cartilage health. By using all 3 of these data sources a more well-rounded picture of each subject's overall well-being.

1.3 Overview of Thesis

This thesis includes 4 chapters. Chapter 2 gives an overview of the methods used in this work to classify MRI results, scored clinical quality of life assessments, and analyze the kinematics that describe subject-specific motion patterns. Also included in Chapter 2 is the description of the analysis procedure used for pair-wise comparisons. Chapter 3 outlines the results of this study from all three paired comparisons as well as a composite analysis. Finally, Chapter 4 includes a discussion of the results found in Chapter 3 as well as the significance of this work. A section in Chapter 4 explores the shortcomings of this study and possible future work that can be done to further explore this topic.

Chapter 2: Methodology

This project is a continuation of a larger study approved by the OSU IRB and funded by the National Football League Charities [9]. 15 NCAA football linemen from Division I through III schools within driving distance of The Ohio State University participated in the initial round of data collection, and 12 returned for evaluation after the conclusion of the season. Each session included magnetic resonance images (MRI) of each knee, 6 self-administered surveys, and a series of tasks performed in the motion capture lab. Of the 12 players who returned for the postseason analysis, 2 failed to complete the series of surveys and 2 others did not have complete sets of movement data. Therefore, a total of 8 complete sets information were used for this study.

In order to organize the subject-specific data, player profiles were created, and each includes 3 sets of pre and postseason data (Figure 5). The first included data set consists of the quantified MRI classifications which indicate the radiological health of the knee cartilage .Next, the clinical quality of life assessments were incorporated, and these illuminate the subjects' opinion of their own overall well-being. Finally, the kinematics from gait trials in the motion capture lab were added to help describe subject-specific movement patterns. These three assessments were combined with the goal of generating a clearer picture of each individual's health and movement.

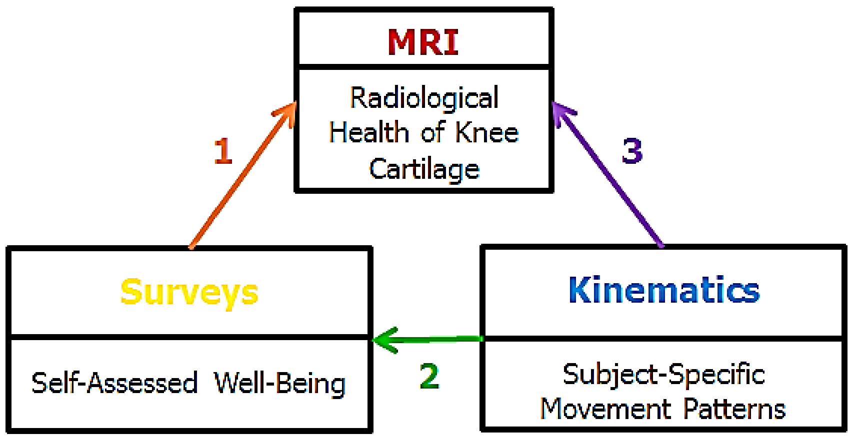

Figure 5: Significance of player profile components

As stated previously, this study utilizes all 3 data groups in the participant profile to help predict or indicate pre to postseason changes in knee cartilage health. While each category adds to the analysis, specific subgroups were selected to focus the scope of this work. These subsets were used for each comparison in the paired analysis (Figure 6).

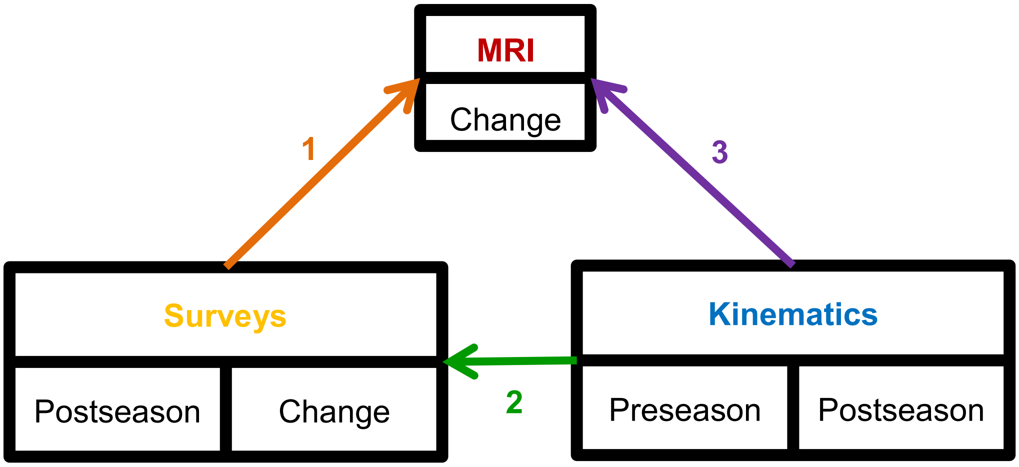

Figure 6: Description of paired analysis process

As stated in the purpose, this study analyzes paired comparisons that are both predictive and indicative of changes in knee cartilage health. Separating Comparisons 1, 2, and 3 into comparisons among subcategories highlights the predictive or indicative nature of each comparison (Table 1). Predictive comparisons include preseason quantities as inputs while indicate comparisons utilize postseason or change variables.

Table 1: Classification of paired comparisons

Comparison	Input	Output	Predictive or Indicative?
1a	Postseason Survey Scores	Change in MRI Classification	Indicative
1b	Change in Survey Scores	Change in MRI Classification	Indicative
2a	Preseason Kinematics	Postseason Survey Scores	Predictive
2b	Postseason Kinematics	Change in Survey Scores	Indicative
2c	Preseason Kinematics	Postseason Survey Scores	Predictive
2d	Postseason Kinematics	Change in Survey Scores	Indicative
3a	Preseason Kinematics	Change in MRI Classification	Predictive
3b	Postseason Kinematics	Change in MRI Classification	Indicative

2.1 MRI

At the start of each session, partnering physicians performed a complete orthopedic exam for each subject. Next, MRI were taken of each of the players' knees using a 3.0T whole body MRI system (Achieva, Phillips Healthcare, Cleveland, OH) and scored by partnering musculoskeletal radiologists according to the Outerbridge classification [9, 10]. This technique grades cartilage health on a scale from 0 to 4. A score of 0 indicates normal, healthy cartilage while a score of 4 describes cartilage with a full-thickness defect and changes to the underlying bone. The cartilage health was scored in 5 separate areas: the lateral patella, medial patella, central lateral femoral condyle (LFC), posterior LFC, and medial tibial plateau [9].

Initially, the Outerbridge Classification was used to score cartilage health in the 5 distinct areas named previously to provide information on the overall health of the cartilage in the knee joint. According to the Outerbridge classifications on the right side, none of the subjects experienced diminishing knee cartilage health from pre to postseason (Table 2). Subject 6 had a grade 3 cartilage defect on the lateral patella, and a grade 1 on the medial patella in the preseason that improved to a grade 0 in the postseason. Due to the inability of cartilage to self-repair, the abnormality on the medial patella was assumed to be the same in the pre and postseason. Subject 6 also had a grade 3 abnormality on the lateral patella which did not change, and subject 10 had a grade 2 defect on the medial patella that remained the same over the course of the season. Based on these results, there was no change in MRI classification in the right knee between the pre and postseason evaluations.

Table 2: Right side Outerbridge classifications from pre to postseason [7]

Subject	Patella (Lateral)	Patella (Medial)	Central LFC	Posterior LFC	Medial Tibia
3	0	0	0	0	0
5	0	0	0	0	0
6	**3**	**1=>0**	0	0	0
8	0	0	0	0	0
10	0	**2**	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0

On the left side, changes in the Outerbridge classifications were present, indicating changes in knee cartilage health (Table 3). On the left side, subjects 6 and 8 had cartilage abnormalities on the medial patella that remained the same over the course of the season. Subjects 3 and 10, however, formed new cartilage abnormalities between the pre and postseason. Subject 3 developed a grade 4, or full thickness, defect on the medial tibial plateau while subject 10 is a grade 2 on the lateral patella. Since the only changes in cartilage health classification were present in the left knee, only the kinematics and MRI classifications for the left side of the body were used for this analysis.

Table 3: Left side Outerbridge classifications from pre to postseason [7]

Subject	Patella (Lateral)	Patella (Medial)	Central LFC	Posterior LFC	Medial Tibia
3	0	0	0	0	**0=>4**
5	0	0	0	0	0
6	0	**1**	0	0	0
8	0	**1**	0	0	0
10	**0=>2**	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0

For the purposes of this analysis, the results of the Outerbridge classifications were simplified to a binary quantity. In the statistical analysis, a decline in the knee cartilage health for any participant corresponds to a 1, while consistent cartilage health becomes a 0 (Table 4).

Table 4: Change in MRI classification for all subjects

Subject	Change in MRI Classification?	Binary Outcome
3	Decline	1
5	None	0
6	None	0
8	None	0
10	Decline	1
13	None	0
14	None	0
15	None	0

2.2 Surveys

After the orthopedic exam and MRI, each of the participants filled out a series of self-administered surveys to assess their perceived quality of life. Six surveys were used in total and each focused on different aspects of the individual's well-being (Table 5).

Table 5: Surveys used to assess self-assessed well-being [11-16]

Survey	Purpose
SF-36v2 Health Survey	Evaluate overall health: physical, emotional, social
IKDC Subjective Knee Evaluation	Assess the efficacy of the treatment of knee ligament injuries
Lysholm Knee Scoring Scale	Determine the efficacy of knee ligament surgery
KOOS Knee Survey	Determine the effect of traumatic knee injury on the development of OA
Kujala Survey	Relate symptoms to objective measures of patellar position analyzed by MRI
Marx Activity Score	Evaluate activity level

Each survey was scored based according to the guidelines laid out in literature and each participant completed the series of surveys during both the pre and postseason evaluations [11-16]. Therefore, preseason, postseason, and change scores were calculated for each survey and each participant. The change score indicates the difference between the pre and postseason score, with a positive change indicating a postseason score greater than that is the preseason.

The Marx Activity Score, for example, has a maximum score of 16, which indicates the highest level of activity (Table 6). In order to score a 16, an individual must determine that he performs the following activities at least 4 times each week: cutting, pivoting, running, and decelerating. The raw scores, specifically the postseason scores and changes from pre to postseason, were used for the remainder of this analysis.

Table 6: Sample Scoring Scheme

Marx Activity Survey			
Subject	Preseason Score	Postseason Score	Difference
3	15	16	1
5	16	9	-7
6	14	16	2
8	16	13	-3
10	11	14	3
13	16	16	0
14	14	16	2
15	14	16	2

2.3 Kinematics

Next, participants were asked to perform a series of tasks in the motion capture laboratory (Figure 7) which included walking, jogging, squatting, and 3 lineman-specific motions. Markers were placed on the subjects' bodies according to the point cluster technique (PCT) (Figure 8), and 10 Vicon MX-F40 cameras at 120 Hz (Vicon; Oxford, UK) tracked the motion of these markers through space during each of the tasks [17]. In addition, 6 Bertec force plates, (Bertec Corp.; Columbus, OH) arranged in a T-formation, were used to capture the ground reaction forces exerted on each player throughout each trial.

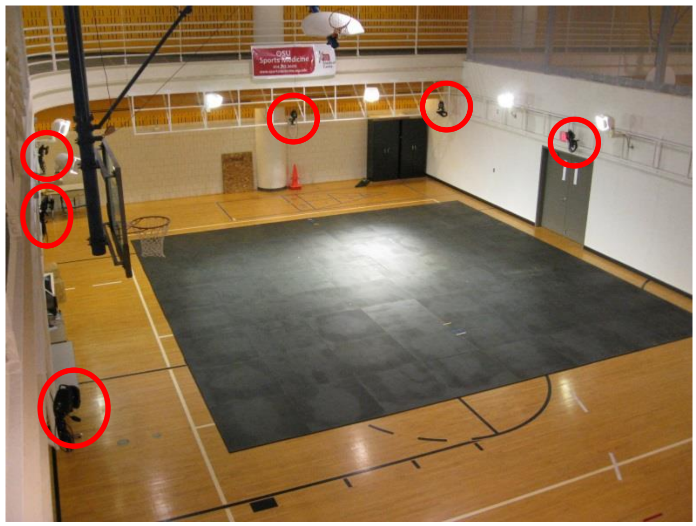

Figure 7: Motion Capture Laboratory at The Ohio State University
Photo courtesy of NMBL

Figure 8: Participant with markers arranged according to PCT
Photo courtesy of NMBL

For this study, the gait, or walking, trials were chosen as the primary focus. Cartilage adapts to repetitive motion patterns; thickening in areas of higher applied pressure and thinning in areas with lesser applied loads. Most people walk more steps over the course of their lifetime than they jog or make sport-specific motions, and therefore, it is reasonable to conclude that the movement patterns in gait are representative of the conditions to which the knee cartilage is conditioned [18]. For this reason, the gait trials are the source of all kinematic data used for this study.

The information from the Vicon cameras included the position of each marker as it moved through space, described by a local reference frame. Vicon Body Builder was used to transform the raw data into usable quantities. For example, the position of all markers in a global reference frame was derived from the local coordinates, and kinetic quantities, such as knee joint angles, were measured from raw data. Next, kinematic quantities were generated in MATLAB: knee joint moments and moment impulses. In order to obtain the normalized ground and joint reactions forces, the output from the force plates was divided by body weight and height. This allowed for the comparison of different variables from the walking trials across different subjects. For these kinematic quantities, both the pre and postseason values were used in the subsequent analysis. In addition, the analysis focused on the motion of the knee and therefore, only knee angles, moments, moment impulses, and reaction forces were considered.

2.4 Paired Comparisons

The analysis process for the paired comparisons included a literature review to support the selection of independent variables from correlation studies. Along with both stepwise and general regressions, these tests were used to quantify the relationships among variables in Comparisons 1, 2, and 3 (Figure 9).

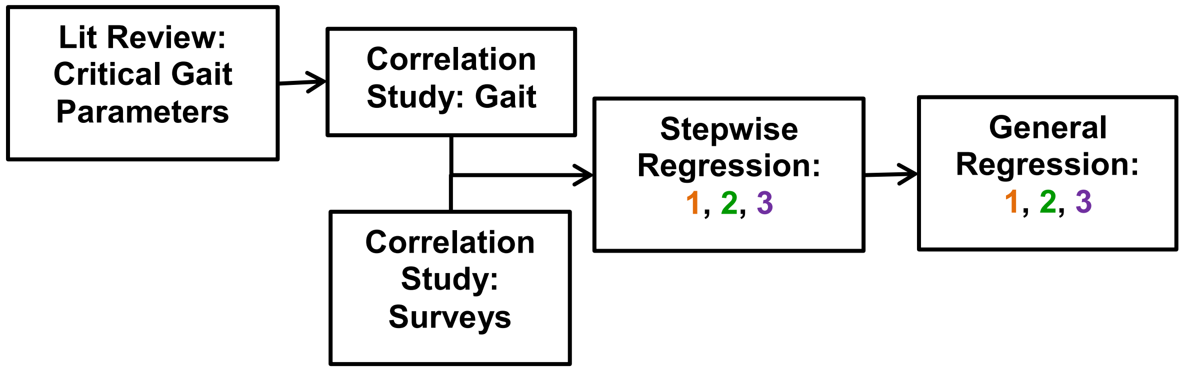

Figure 9: Statistical analysis process

It has been shown that individuals with cartilage defects are more likely to develop more severe or early-onset OA in that joint than their age-matched controls [2]. Therefore, the first step in the analysis process included a review of studies highlighting the changes in walking patterns between groups with OA and healthy age-matched controls. These studies examine differences in kinematic variable among the two groups to identify characteristic trends, such as slower self-selected walking speeds in OA groups compared to healthy controls [19, 20]. These differences were considered critical kinematic gait parameters for this analysis and were used to identify relevant groups of kinematic variables (Table 7).

Table 7: Summary of critical parameters from literature review

Comparison of Critical Gait Parameters between subject with OA and Age-Matched Controls	
Critical Variables	**OA Group _____ than Control**
Walking Speed	Less
Stride Time	Greater
Flexion Angle	Less
Adduction Angle	Greater
Abduction Angle	Greater
Extension Moment	Greater
Flexion Moment	Less
Abduction Moment	Greater
Internal Rotation Moment	Greater
Vertical Joint Reaction Force	Less
Vertical Ground Reaction Force	Less

After the literature review, a correlation study was performed to illuminate the interdependence of input variables: pre and postseason kinematic variables as well as postseason and changes in survey variables. It is important that the variables considered as inputs for statistical analysis were not dependent on one another. Using 2 variables that depend on one another may lead to conclusions based on the relationship between the 2 inputs rather than the relationship between one input and one output. The relationships among input variables are not of primary interest in this study and therefore, only independent parameters were used for each statistical test. In order to obtain these independent variables one correlation study was performed for each group of variables: preseason kinematics, postseason kinematics, postseason survey scores, and changes in survey scores. If the p-value describing the relationship between 2 variables was less than 0.1, they were considered to be independent of one another and both were required for a complete analysis. If the p-value was greater than 0.1, the two variables were considered to depend on one another and therefore, only one was necessary for a complete analysis.

First, correlation studies were used to examine the relationships among postseason survey scores and changes in scores from pre to postseason. This comparison yielded 9 groups of independent survey variables for both the postseason and change analyses. The 3 most relevant groups, which were used for further analysis, were chosen because they included the greatest number of variables. When repeating the analysis for the pre and postseason kinematic variables, the most appropriate groups of variables were chosen using the results of the literature review. The parameters that had been defined as "critical" were highlighted in each group, and the 4 groups with the greatest number of critical parameters were used in the regression analyses.

Next, a stepwise regression with n=8, alpha-in=0.15, and alpha-out=0.15 was performed (Table 8). Only the first two steps of each regression were considered due to the small sample size (n=8). This limit helped to keep the results within the boundaries of the given parameters and sample size.

Table 8: Outline of pairs used in the regression analysis

Comparison	Predictors/Indicators (Input)	Response (Output)
1a	Postseason Survey Scores	Change in MRI Classification
1b	Change in Survey Scores	Change in MRI Classification
2a	Preseason Kinematics	Postseason Survey Scores
2b	Postseason Kinematics	Change in Survey Scores
2c	Preseason Kinematics	Postseason Survey Scores
2d	Postseason Kinematics	Change in Survey Scores
3a	Preseason Kinematics	Change in MRI Classification
3b	Postseason Kinematics	Change in MRI Classification

Finally a general regression was used to validate the results of each stepwise regressions. For this step, the variables identified in the first two steps of the stepwise regression were used as inputs with the same output that was used previously. A p-value less than 0.05 indicated a statistically significant input variable. In addition, the regression coefficient was used to describe the relationship between the input and output variables. For example, a positive regression coefficient corresponds to a proportional relationship between the input and an output variable with a negative coefficient indicates an inverse proportional relationship. The regression coefficient also indicated the magnitude of the slope of the curve generated with the input variable on the x-axis and the output on the y-axis. Larger regression coefficients indicate steeper slopes and thereby, more pronounced relationships between input and output variables.

Chapter 3: Results

3.1 Correlation Studies

Four distinct correlation studies were used for this study. The first analysis examined the relationships among the postseason survey variables. These variables correspond to the results of the SF-36v2, IKDC, Lysholm, Kujala, Marx, and the 6 subsets of the KOOS survey: symptoms, stiffness, pain, activities of daily living, sports & recreation, and quality of life. Three groups of postseason variables were used in Comparison 1a which investigates the indicative power of the postseason survey scores in showing changes in MRI classification and subsequently knee cartilage health (Table 9, 10, 11).

Table 9: Largest group of postseason survey variables for Comparison 1a

Postseason Survey Group A (Post Survey A)
SF-36v2
IKDC
Lysholm
Marx
KOOS: Symptoms
KOOS: Stiffness
KOOS: Pain
KOOS: Activities of Daily Living
KOOS: Sports and Recreation
KOOS: Quality of Life

Table 10: Group of postseason survey variables for Comparison 1a

Postseason Survey Group B (Post Survey B)
IKDC
Lysholm
Kujala
KOOS: Symptoms
KOOS: Stiffness
KOOS: Activities of Daily Living

Table 11: Group of postseason survey variables for Comparison 1a

Postseason Survey Group C (Post Survey C)
Lysholm
Kujala
Marx
KOOS: Symptoms
KOOS: Stiffness
KOOS: Pain
KOOS: Activities of Daily Living
KOOS: Sports and Recreation
KOOS: Quality of Life

Next, the variables describing the changes in survey scores from pre to postseason were entered into a second correlation study. From the results of this process, 3 groups of surveys were chosen based on their inclusion of the largest number of survey variables. These 3 groups were used in Comparison 1b which relates the changes in MRI classification and the changes in survey scores (Table 12, 13, 14).

Table 12: Largest group of change in survey score variables for Comparison 1b

Change in Survey Score Group A (Change Survey A)
SF-36v2
IKDC
Lysholm
Kujala
Marx
KOOS: Symptoms
KOOS: Stiffness
KOOS: Pain
KOOS: Activities of Daily Living
KOOS: Sports and Recreation
KOOS: Quality of Life

Table 13: Second group of change in survey score variables for Comparison 1b

Change in Survey Score Group B (Change Survey B)
IKDC
Lysholm
KOOS: Stiffness
KOOS: Activities of Daily Living

Table 14: Third group of change in survey score variables for Comparison 1b

Change in Survey Score Group C (Change Survey C)
Lysholm
Kujala
Marx
KOOS: Symptoms
KOOS: Stiffness
KOOS: Pain
KOOS: Activities of Daily Living
KOOS: Sports and Recreation
KOOS: Quality of Life

The third correlation study focused on the kinematic variables from the walking trials in the motion capture laboratory. The preseason variables were divided into groups of independent parameters. 4 different groups were utilized in both Comparison 2, between survey results and kinematic parameters, and Comparison 3, which examines the relationship between changes in MRI classification and kinematic parameters. These groups were chosen based on their inclusion of parameters considered to be “critical” during the literature review (Table 15, 16, 17).

Table 15: Preseason gait kinematics group A for Comparisons 2 and 3

Preseason Kinematics Group A (Pre Kin A)
Speed
Stance Time
Flexion Angle
Extension Angle
Adduction Angle
Abduction Angle
Internal Rotation Angle
External Rotation Angle
1st Adduction Moment
2nd Adduction Moment
Abduction Moment
Flexion Moment
1st Extension Moment
2nd Extension Moment
Internal Rotation Moment
External Rotation Moment
Adduction Impulse
Abduction Impulse
Flexion Impulse
Extension Impulse
Internal Rotation Impulse
External Rotation Impulse
Vertical Joint Reaction Force

Table 16: Preseason gait kinematics group B for Comparisons 2 and 3

Preseason Kinematics: Group B (Pre Kin B)
Stance Time
Flexion Angle
Extension Angle
Adduction Angle
Abduction Angle
External Rotation Angle
1st Adduction Moment
2nd Adduction Moment
Flexion Moment
1st Extension Moment
2nd Extension Moment
Internal Rotation Moment
External Rotation Moment
Adduction Impulse
Flexion Impulse
Extension Impulse
Internal Rotation Impulse
External Rotation Impulse

Table 17: Preseason gait kinematics group C for Comparisons 2 and 3

Preseason Kinematics: Group C (Pre Kin C)
Flexion Angle
Extension Angle
Adduction Angle
Abduction Angle
Internal Rotation Angle
External Rotation Angle
1st Adduction Moment
2nd Adduction Moment
1st Extension Moment
2nd Extension Moment
Internal Rotation Moment
Adduction Impulse
Internal Rotation Impulse
External Rotation Impulse
Vertical Joint Reaction Force

Finally, the postseason kinematic parameters were input into a correlation study. These quantities were utilized in both Comparison 2, between surveys and kinematic parameters, and Comparison 3, which examines the relationship between changes in MRI classification and kinematic parameters. The 4 groups of variables used in the stepwise regression analysis were chosen based on their inclusion of "critical" parameters defined during the literature review (Table 18, 19, 20, 21).

Table 18: Postseason gait kinematics group A for Comparisons 2 and 3

Postseason Kinematics: Group A (Post Kin A)
Speed
Stance Time
Flexion Angle
Extension Angle
Adduction Angle
Abduction Angle
Internal Rotation Angle
External Rotation Angle
2nd Adduction Moment
Abduction Moment
Flexion Moment
Internal Rotation Moment
External Rotation Moment
Adduction Impulse
Abduction Impulse
Flexion Impulse
Internal Rotation Impulse
External Rotation Impulse

Table 19: Postseason gait kinematics group B for Comparisons 2 and 3

Postseason Kinematics: Group B (Post Kin B)
Stance Time
Flexion Angle
Extension Angle
Adduction Angle
Internal Rotation Angle
External Rotation Angle
1st Adduction Moment
2nd Adduction Moment
Abduction Moment
Flexion Moment
1st Extension Moment
2nd Extension Moment
Internal Rotation Moment
External Rotation Moment
Adduction Impulse
Abduction Impulse
Flexion Impulse
Extension Impulse
Internal Rotation Impulse
External Rotation Impulse

Table 20: Postseason gait kinematics group C for Comparisons 2 and 3

Postseason Kinematics: Group C (Post Kin C)
Flexion Angle
Extension Angle
Adduction Angle
Abduction Angle
Internal Rotation Angle
External Rotation Angle
2nd Adduction Moment
Abduction Moment
Flexion Moment
1st Extension Moment
2nd Extension Moment
External Rotation Moment
Abduction Impulse
Flexion Impulse
Extension Impulse
External Rotation Impulse
Vertical Joint Reaction Force

Table 21: Postseason gait kinematics group D for Comparisons 2 and 3

Postseason Kinematics: Group D (Post Kin D)
Extension Angle
Adduction Angle
Abduction Angle
Internal Rotation Angle
External Rotation Angle
1st Adduction Moment
2nd Adduction Moment
Abduction Moment
Flexion Moment
1st Extension Moment
Internal Rotation Moment
External Rotation Moment
Adduction Impulse
Abduction Impulse
Flexion Impulse
Internal Rotation Impulse
External Rotation Impulse
Vertical Joint Reaction Force

3.2 Results of Comparison 1 (MRI and Surveys)

Comparison 1 explores the relationship between the changes in MRI classification corresponding to changes in cartilage health and the results from the clinical quality of life assessments. First, the postseason survey results were compared to the changes in MRI classification. Beginning with a stepwise regression, the 3 groups of independent postseason survey variables were used as the input parameters and the binary quantities corresponding to changes in MRI were the output variables. Next, the process was repeated using the 3 groups of variables describing the change in survey scores from pre to post season. For both of these analyses, only the first input group yielded variables that may be statistically significant indicators of changes in MRI classification. The postseason Marx Activity Score, changes in the SF-36v2 score, and changes in the KOOS: Stiffness subscore were identified in these analyses (Table 22).

Table 22: Results of Stepwise Regression for Comparison 1 (MRI and Survey)

Input Group	Step	Input Variable	Output Variable	P-Value
Post Survey A	1	Postseason Marx Activity Score	Change in MRI Classification	0.036
Change Survey A	1	Change in SF-36v2 Score	Change in MRI Classification	0.003
	2	Change in KOOS: Stiffness Score		0.067

After the stepwise regressions, the potentially significant variables were used in a single step general regression analysis. This regression was used to validate the results found in the stepwise regressions and quantifies the relationships between the survey variables and changes in MRI classification. For Comparison 1, the postseason Marx Activity Score and change in the SF-36 scores were statistically significant indicators of changes in MRI classification (Table 23).

Table 23: General regression analysis for surveys and MRI

<table>
<tr><th>Predictor/Indicator</th><th>Response</th><th>P-value</th><th>Regression Coefficient</th><th>R^2 Value</th><th>Adjusted R^2 Value</th></tr>
<tr><td>Postseason Marx Activity Score</td><td rowspan="3">Change in MRI Classification</td><td>0.036</td><td>-0.136</td><td>54.55%</td><td>46.97%</td></tr>
<tr><td>Change in SF-36v2 Score</td><td>0.028</td><td>0.105</td><td rowspan="2">86.74%</td><td rowspan="2">76.79%</td></tr>
<tr><td>Change is KOOS: Stiffness Score</td><td>0.119</td><td>0.0129</td></tr>
</table>

Based on the regression coefficients from the general regression validations, it was shown that the postseason Marx Activity score and the change in MRI classification were inversely proportional. Therefore, as the classification of MRI readings increased, or the knee cartilage health declined, the postseason Marx score was decreasing, showing a decrease in the amount of activity performed by the individual. The change in SF-36 score, however, was directly proportional to the change in MRI classification. This indicates an increase in the difference between pre and postseason SF-36 scores as cartilage health declines.

3.3 Results of Comparison 2 (Surveys and Kinematics)

Comparison 2 examines the relationship between pre and postseason kinematic parameters from walking trials in the motion capture lab and the survey variables identified as significant in Comparison 1: postseason Marx Activity Score and the change in SF-36 score. First, the 3 groups of preseason kinematic variables were compared to both the postseason Marx score and change in the SF-36 score using a stepwise regression. From this analysis, the preseason self-selected walking speed and the 1^{st} knee extension moment were identified as potentially significant by this regression for the postseason Marx Activity Score (Table 24).

Table 24: Summary of stepwise regression for preseason kinematics and surveys

Input Group	Step	Preseason Input Variables	Output Variable	P-Value
Pre Kin A	1	Speed	Postseason Marx Activity Score	0.011
	2	1st Extension Moment		0.029

Next, the same analysis was repeated using the 4 groups of independent postseason kinematic variables identified previously. In this case, the stepwise regression showed the knee flexion moment and extension angle as potentially significant indicators of changes in the postseason Marx Activity Score in all 4 tests. This same analysis pointed out 6 different variables that may be significant indicators of changes in the SF-36 scores from preseason to postseason (Table 25).

Table 25: Summary of stepwise regression for postseason kinematics and surveys

Input Group	Step	Postseason Input Variables	Output Variable	P-Value
Post Kin A-D	1	Flexion Moment	Postseason Marx Activity Score	0.001
	2	Extension Angle		0.006
Post Kin A	1	Flexion Angle	Change in SF-36 Score	0.012
	2	Speed		0.046
Post Kin B	1	Flexion Angle		0.007
	2	1st Adduction Moment		0.027
Post Kin C	1	Flexion Angle		0.035
	2	Flexion Moment Impulse		0.088
Post Kin D	1	Internal Rotation Moment Impulse		0.052
	2	Internal Rotation Moment		0.141

Next, two discrete general regressions were used to validate the findings from the stepwise regression. First, the preseason kinematic variables were compared to the postseason survey scores. It was determined that the preseason self-selected walking speed and 1st Knee Extension Moment were significant indicators of the postseason Marx activity score. Next, the postseason analysis showed that the postseason knee extension angle and flexion moment are also significant indicators of the postseason Marx Activity Scores (Table 26). None of the pre or postseason variables pointed out in the stepwise regressions was a significant indicator of the changes in SF-36 scores.

Table 26: General regression validation of stepwise regression for surveys and kinematics

Predictor/Indicator	Response	P-value	Regression Coefficient	R^2 Value	Adjusted R^2 Value
Preseason Speed	Postseason Marx Activity Score	0.011	-0.0258	76.21%	66.70%
Preseason 1st Knee Extension Moment		0.029	-2.169		
Postseason Knee Extension Angle	Postseason Marx Activity Score	0.006	-0.532	90.00%	85.99%
Postseason Flexion Moment		0.001	16.885		

Based on the regression coefficients for the preseason speed and 1st extension moments, these quantities are shown to have inversely proportional relationships with the postseason Marx score. As the postseason Marx score increases, or an individual's activity level increases, the self-selected walking speed and 1st knee extension moment decrease. In addition, the postseason knee extension angle was inversely proportion to the postseason score. This shows that as an individual's activity level increases, the knee extension angle decreases. Finally, the postseason flexion moment is proportional to the postseason Marx score. So, as an individual becomes more active, his knee flexion moment increases.

3.4 Results of Comparison 3 (MRI and Kinematics)

Comparison 3 examines the relationship between kinematic variables from the walking trials and changes in the classification of knee cartilage health as evaluated by MRI. First, the 3 groups of independent preseason kinematic parameters were compared to changes in MRI classifications. This analysis showed that the preseason knee external rotation angle and flexion moment impulse were potentially significant predictors of changes in MRI classification corresponding to changes in knee cartilage health. Then, the analysis was repeated using the 4 postseason groups. In this case, the postseason flexion angle, abduction moment, flexion moment, and vertical joint reaction (VJRF) were potentially significant indicators of changes in MRI classifications as they were accepted in the first two steps of the stepwise regression (Table 27).

Table 27: Stepwise regression results for kinematics and MRI

Input Group	Step	Input Variable	Output Variable	P-Value
Pre Kin A & B	1	Preseason External Rotation Angle	Change in MRI Classification	0.027
	2	Preseason Flexion Moment Impulse		0.048
Pre Kin C	1	Preseason External Rotation Angle		0.112
Post Kin A-C	1	Postseason Flexion Angle	Change in MRI Classification	0.007
	2	Postseason Abduction Moment		0.013
Post Kin D	1	Postseason Flexion Moment		0.047
	2	Postseason VJRF		0.136

A general regression was used once again to validate the findings from the stepwise regressions. First, the preseason gait kinematics and changes in MRI classification were compared. This analysis yielded two statistically significant predictors of the changes in knee cartilage health: preseason knee external rotation angles and flexion moment impulses. Based on the regression coefficients from the preceding analysis the preseason knee external rotation angle was inversely proportional to the change in MRI classification. Therefore, as an individual's knee cartilage health declines, and classification increases, the external rotation angle decreases. The preseason flexion moment, however, is directly proportional to the changes in MRI score. This means that as cartilage health declines, an individual's knee flexion moment impulse during gait increases. Next, the general regression was performed using the postseason kinematic variables and MRI information. In this case, both the postseason knee flexion angle and abduction moment were found to statistically significant indicators of changes in knee cartilage health (Table 28). Both the postseason knee flexion angle and abduction moment are directly proportional to the change in MRI classification. As cartilage health declines, therefore, the postseason knee flexion angle and abduction moment decrease.

Table 28: General regression validation of stepwise regression for kinematics and MRI

<table>
<tr><th>Predictor/Indicator</th><th>Response</th><th>P-value</th><th>Regression Coefficient</th><th>R^2 Value</th><th>Adjusted R^2 Value</th></tr>
<tr><td>Preseason External Rotation Angle</td><td rowspan="4">Change in MRI Classification</td><td>0.026</td><td>-0.0772</td><td rowspan="2">73.00%</td><td rowspan="2">62.20%</td></tr>
<tr><td>Preseason Flexion Moment Impulse</td><td>0.027</td><td>2.000</td></tr>
<tr><td>Postseason Flexion Angle</td><td>0.003</td><td>1.215</td><td rowspan="2">93.83%</td><td rowspan="2">89.20%</td></tr>
<tr><td>Postseason Abduction Moment</td><td>0.005</td><td>1.544</td></tr>
</table>

Chapter 4: Discussion and Conclusions

For the discussion of these results, it is assumed that a change in the MRI classification of an area of knee cartilage presents the same kinematic abnormalities as OA. Therefore, the findings from the literature review were used as a basis for generating a set of expected results.

4.1 Discussion of Comparison 1 (MRI and Survey)

As the health of articular cartilage in the knee declines, it is expected that the affected individual will decrease their level of activity. Previous work has shown that individuals with OA report diminished quality of life metrics and lower activity levels than healthy, age-matched controls [2]. Therefore, it was expected that an increase in the classification of an MRI due to a decline in cartilage health would correspond to a decrease in the postseason Marx Activity Scores. This expectation was confirmed by the work in this study. The postseason Marx score was determined to be statistically significant indicator of changes in knee cartilage health. In addition, the negative regression coefficient indicates that a decline in cartilage health corresponds to decreased levels of activity.

The second portion of Comparison 1 investigated the relationship between changes in cartilage health and the difference between pre and postseason SF-36 scores (Figure 10). Based on the regression coefficient, an increase in the change between pre and postseason SF-36 scores indicates a decline in cartilage health. A change in survey score is defined as the preseason score subtracted from the postseason score. Therefore, a positive change in SF-36 scores shows that the postseason value was greater than the preseason score and the subject's reported social, emotional, and physical well-being improved in the time between evaluations. A negative change demonstrates a score that decreases over the course of the season. In this case, an increase in the SF-36 change variable indicates a higher postseason score, a lower preseason score, or both. Based on these definitions, an increase in the change in SF-36 scores may correspond to a postseason value that either improves or declines compared to the preseason and on the connection between changes in MRI classification and the SF-36 scores. Therefore, no definitive conclusion can be drawn.

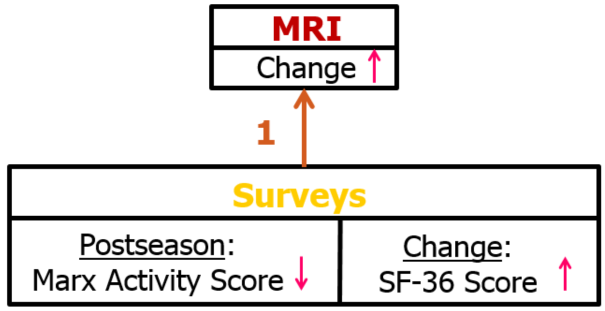

Figure 10: Results of Comparison 1 (MRI and surveys)

4.2 Discussion of Comparison 2 (Surveys and Kinematics)

The Comparison 2 examined the relationship between kinematic parameters and clinical quality of life metrics. For this discussion, a decline in Marx score corresponds to a decline in knee cartilage health. An individual with a cartilage defect was assumed to exhibit the same kinematic abnormalities as someone with OA.

The preseason analysis showed that that both self-selected walking speed and the 1st knee extension moment were both statistically significant predictors of changes in knee cartilage health. Regression coefficients indicate that, for this analysis, as the postseason Marx score decreases, an individual's self-selected walking speed increases. This directly opposes the findings in OA studies where those with diminished knee health walk more slowly than the healthy controls [19, 20]. In addition, this portion of the analysis suggests that a decrease in postseason Marx score corresponds with an increase in the 1st knee extension moment. This result aligns with the anticipated results since individuals with OA often generate larger extension moments as their joint health decreases [19].

The postseason portion of this analysis indicates that as the postseason Marx score decreases, the subjects' knee flexion angles and flexion moments both increase (Figure 11). This directly contradicts previous work that shows that individuals with diminished knee cartilage health experience a decrease in knee flexion angles and flexion moments [19, 20].

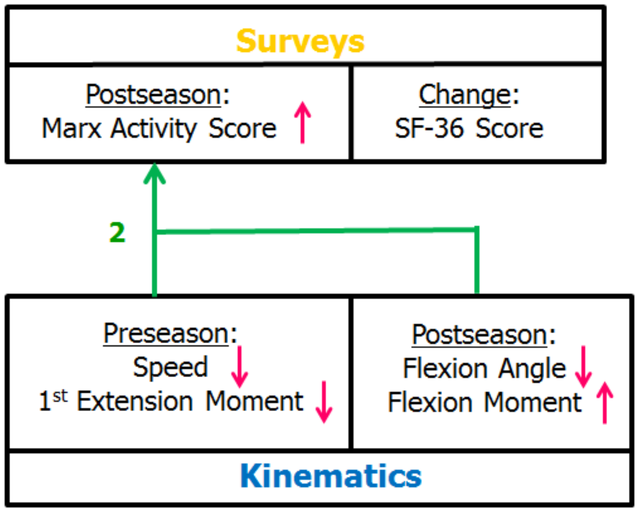

Figure 11: Results of Comparison 2 (Surveys and Kinematics)

4.3 Discussion of Comparison 3 (MRI and Kinematics)

Comparison 3 investigated the relationships between pre and postseason gait kinematics and changes in knee cartilage health. In the preseason portion of this comparison, the knee external rotation angle was found to decrease as the MRI classification increased and cartilage health decreased [19, 20]. In addition, the knee flexion moment impulse was shown to increase as the change in MRI classification increased. While moment impulses were not found to be significant in previous work with OA populations, these works found that the knee flexion moment and self-selected walking speed decreased for individuals with OA [19]. Moment impulses are defined as $J = \frac{M}{t}$ where J is the moment impulse, M is the joint moment, and t is time. Previous work shows that the knee joint flexion moment and speed decrease for OA groups [19]. This means that time increases and the magnitude of the flexion moment decreases; thereby decreasing the magnitude of the entire ratio. Therefore, individuals with OA should experience a decrease in knee flexion moment impulse as their knee cartilage health worsens. In this study, however, it was found that the knee flexion moment increases as the knee cartilage health declines.

In the postseason portion of the analysis, it was shown that an increase in knee flexion angle and decrease in knee abduction moment correspond to a decline in knee cartilage health. These results are the opposite of the expected relationship, based on the literature review [19, 20].

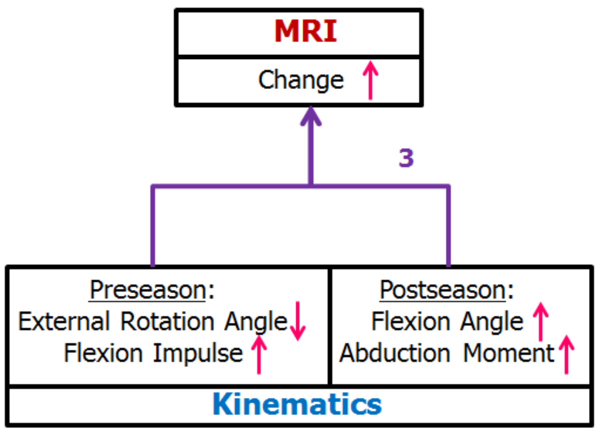

Figure 12: Results of Comparison 3 (MRI and Kinematics)

4.3 Overall Result

This analysis yields an interconnected web of parameters that may predict or indicate changes in knee cartilage health. The classification of MRI was used to quantify knee cartilage health and this analysis focuses of parameters that predict of indicate changes in these classifications (Figure 13).Due to the small sample size (n=8), this work should be used as a guide for future research than a basis for independent conclusions.

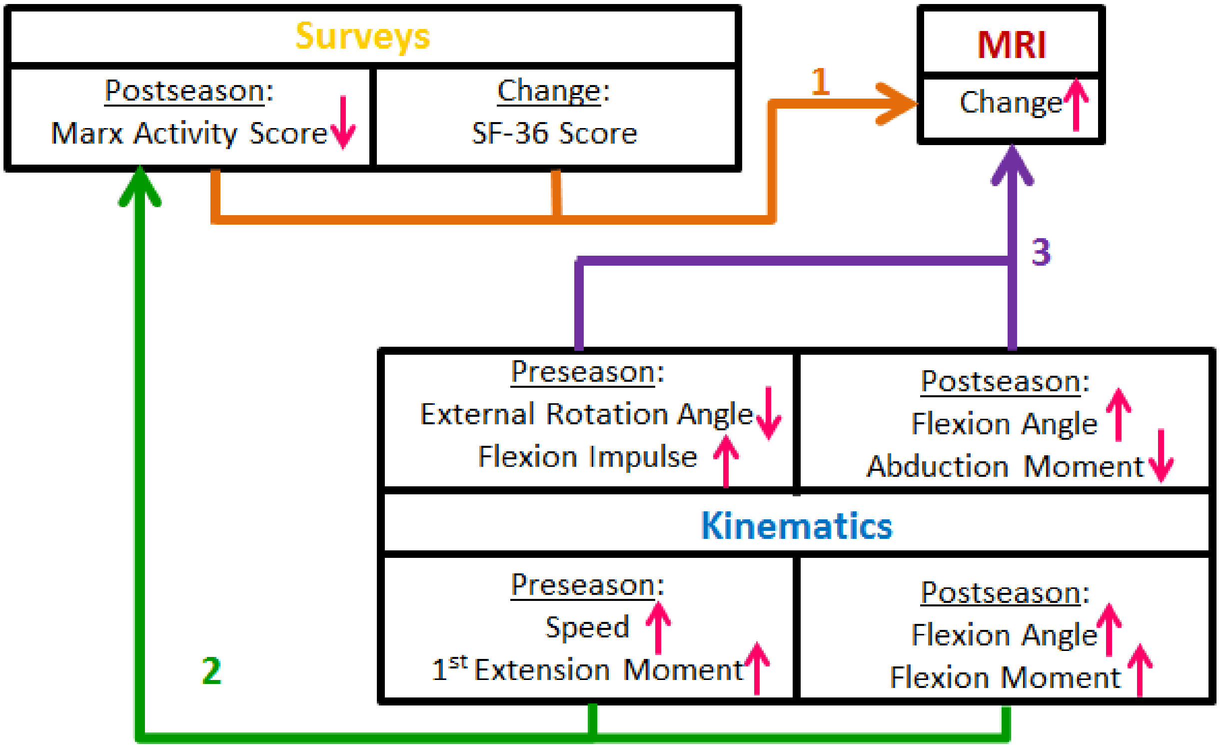

Figure 13: Map of overall results for all 3 comparisons

4.5 Clinical Significance

This study is a foundation for future work which can define key parameters that indicate or predict changes in knee cartilage health; eventually creating a guide for clinicians that justifies further investigation. For example, if certain quantities such as self-selected walking speed fall outside of the acceptable ranges as determined by experimental methods, then clinicians may perform additional tests to examine the health of a joint.

4.5 Shortcomings and Future Work

Due to its limitations, the results from this survey cannot be used to draw definitive conclusions about the behavior of individuals with knee cartilage defects. First, this study is based on a sample size of 8 subjects were only 2 showed changes in their knee cartilage health over the course of the season. Therefore, these results may show changes or abnormalities that are unique to this population. In the future, a larger study with a greater number of participants should be conducted to further explore the effects of one season of play on the knee cartilage health of football linemen. This study should not only include a greater number of participants, but should recruit individuals over a larger range of ages and with different amounts of playing experience. By continuing this work over several years, the incremental effect of each season on cartilage health may be made clearer.

This study is also limited by the subgroups chose for the paired comparisons. There are many different comparisons that may be made by including changes in kinematic parameters as well as preseason survey scores. This can lead to more concrete conclusions regarding the effects of one season on knee cartilage health. In addition, future studies should focus on exploring a smaller group of parameters or relationships. This consolidation will allow for more relevant analyses and more definitive conclusions.

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Appendix A: Composite Survey Results

Table A 1: SF-36v2 Scores

Subject	Preseason SF-36 Score	Postseason SF-36 Score	Change in SF-36 Score
3	91.250	91.389	0.139
5	78.889	88.889	10
6	91.944	89.306	-2.638
8	96.667	93.889	-2.778
10	83.611	87.639	4.028
13	89.167	90.556	1.389
14	84.306	81.471	-2.835
15	90.000	90.833	0.833

Table A 2: IKDC Subjective Knee Evaluation Scores

Subject	Preseason IKDC Score	Postseason IKDC Score	Change in IKDC Score
3	100.0000	96.5517	-3.4483
5	89.6552	100.0000	10.3448
6	97.7011	89.6552	-8.0459
8	97.7011	94.2529	-3.4482
10	90.8046	91.9540	1.1494
13	100.0000	100.0000	0
14	96.5517	98.7241	2.1724
15	97.7011	88.5057	-9.1954

Table A 3: Lysholm Knee Scoring Scale Scores

Subject	Preseason Lysholm Score	Postseason Lysholm Score	Change in Lysholm Score
3	100	95	-5
5	95	100	5
6	100	100	0
8	100	95	-5
10	95	92	-3
13	100	95	-5
14	97	100	3
15	100	94	6

Table A 4: Kujala Survey Scores

Subject	Preseason Kujala Score	Postseason Kujala Score	Change in Kujala Score
3	100	98	-2
5	98	100	2
6	100	98	-2
8	100	95	-5
10	98	100	2
13	100	100	0
14	95	100	5
15	100	95	-5

Table A 5: Marx Activity Scores

Subject	Preseason Marx Score	Postseason Marx Score	Change in Marx Score
3	15	16	1
5	16	9	-7
6	14	16	2
8	16	13	-3
10	11	14	3
13	16	16	0
14	14	16	2
15	14	16	2

Table A 6: KOOS Knee Survey: Symptom Scores

Subject	Preseason KOOS Symptom Score	Postseason KOOS Symptom Score	Change in KOOS Symptom Score
3	100.000	100.000	0
5	90.000	100.000	10
6	100.000	90.000	-10
8	95.000	95.000	0
10	90.000	85.000	-5
13	100.000	100.000	0
14	90.000	100.000	10
15	100.000	95.000	-5

Table A 7: KOOS Knee Survey: Stiffness Scores

Subject	Preseason KOOS Stiffness Score	Postseason KOOS Stiffness Score	Change in KOOS Stiffness Score
3	100.000	75	-25
5	87.500	75	-12.5
6	100.000	100	0
8	75.000	87.5	12.5
10	87.500	100	12.5
13	100.000	100	0
14	100.000	100	0
15	100.000	75	-25

Table A 8: KOOS Knee Survey: Pain Scores

Subject	Preseason KOOS Pain Score	Postseason KOOS Pain Score	Change in KOOS Pain Score
3	100	88.889	-11.111
5	100	100	0
6	96.556	91	-5.556
8	100	94.444	-5.556
10	97.222	97.222	0
13	100	100	0
14	94.444	100	5.556
15	99.997	91.667	-8.33

Table A 9: KOOS Knee Survey: Activities of Daily Living Scores

Subject	Preseason KOOS Daily Score	Postseason KOOS Daily Score	Change in KOOS Daily Score
3	100	97.059	-2.941
5	100	100	0
6	100	100	0
8	100	100	0
10	100	100	0
13	100	100	0
14	98.529	100	1.471
15	100	94.118	-5.882

Table A 10: KOOS Knee Survey: Sports & Recreation Scores

Subject	Preseason KOOS Sport Score	Postseason KOOS Sport Score	Change in KOOS Sport Score
3	100	100	0
5	80	100	20
6	100	95	-5
8	100	95	-5
10	90	95	5
13	100	100	0
14	85	100	15
15	100	85	-15

Table A 11: KOOS Knee Survey: Quality of Life Scores

Subject	Preseason KOOS Quality Score	Postseason KOOS Quality Score	Change in KOOS Quality Score
3	100	93.75	-6.25
5	100	100	0
6	100	75	-25
8	93.75	87.5	-6.25
10	87.5	81.25	-6.25
13	100	100	0
14	100	100	0
15	100	81.25	-18.75

Appendix B: Complete Results from Regression Analyses

Table B 1: Complete results set from stepwise regressions in Comparison 1

Input Group	Step	Input Variable	Output Variable	P-Value
Post Survey A	1	Postseason Marx Activity Score	Change in MRI Classification	0.036
Post Survey B	1	None		N/A
Post Survey C	1	None		N/A
Change Survey A	1	Change in SF-36v2 Score	Change in MRI Classification	0.003
	2	Change in KOOS: Stiffness Score		0.067
Change Survey B	1	None		N/A
Change Survey C	1	None		N/A

Table B 2: Complete results set from stepwise regressions in Comparison 2

Input Group	Step	Preseason Input Variables	Output Variable	P-Value
Pre Kin A	1	Speed	Postseason Marx Activity Score	0.011
	2	1st Extension Moment		0.029
Pre Kin B	1	None		N/A
Pre Kin C	1	None		N/A
Pre Kin A	1	None	Change in SF-36 Score	N/A
Pre Kin B	1	None		N/A
Pre Kin C	1	None		N/A
Pre Kin D	1	None		N/A

Table B 3: Complete results from the second set of stepwise regressions in Comparison 2

Input Group	Step	Postseason Input Variables	Output Variable	P-Value
Post Kin A	1	Flexion Moment	Postseason Marx Activity Score	0.001
	2	Extension Angle		0.006
Post Kin B	1	Flexion Moment		0.001
	2	Extension Angle		0.006
Post Kin C	1	Flexion Moment		0.001
	2	Extension Angle		0.006
Post Kin D	1	Flexion Moment		0.001
	2	Extension Angle		0.006
Post Kin A	1	Flexion Angle	Change in SF-36 Score	0.012
	2	Speed		0.046
Post Kin B	1	Flexion Angle		0.007
	2	1st Adduction Moment		0.027
Post Kin C	1	Flexion Angle		0.035
	2	Flexion Moment Impulse		0.088
Post Kin D	1	Internal Rotation Moment Impulse		0.052
	2	Internal Rotation Moment		0.141

Table B 4: Summary of results from stepwise regression analyses in Comparison 3

Input Group	Step	Input Variable	Output Variable	P-Value
Pre Kin A	1	Preseason External Rotation Angle	Change in MRI Classification	0.027
	2	Preseason Flexion Moment Impulse		0.048
Pre Kin B	1	Preseason External Rotation Angle		0.027
	2	Preseason Flexion Moment Impulse		0.048
Pre Kin C	1	Preseason External Rotation Angle		0.112
Post Kin A	1	Postseason Flexion Angle	Change in MRI Classification	0.007
	2	Postseason Abduction Angle		0.013
Post Kin B	1	Postseason Flexion Angle		0.007
	2	Postseason Abduction Moment		0.013
Post Kin C	1	Postseason Flexion Angle		0.007
	2	Postseason Abduction Moment		0.013
Post Kin D	1	Postseason Flexion Moment		0.047
	2	Postseason VJRF		0.136